System for Dual Diversity Receiver using Switched LNAs

5   ## FIELD OF THE INVENTION

The present invention relates generally to wireless receivers, and more particularly, to a wireless receiver system that employs multiple antennas and a switching system to switch between two low-noise amplifiers based on the stronger antenna signal.

10   ## BACKGROUND OF THE INVENTION

The radio interface is unique to wireless communication systems and is responsible for much of the complexity associated with these systems. The radio communication channel is affected by large and small-scale fading phenomena. The large-scale phenomena are due to the attenuation of the transmitted signal as it travels through the atmosphere. The small-scale effects depend on multipath propagation due to

15   reflections, diffraction and scattering, and behave unpredictably, leading to sharp and quick variations of the signal strength over small distances.

Therefore, it would advantageous to have a receiver system that is able to compensate for the effects of large and small-scale fading phenomena.

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SUMMARY OF THE INVENTION

In one or more embodiments, a dual diversity receiver system is provided that selects the stronger of two received signals. The receiver system comprises a switched low noise amplifier (LNA) to interface to each of two antennas, and selection logic that

25   performs a switching algorithm to periodically check the received signal power of each antenna to select the stronger signal. In one embodiment, the LNAs are switched to the alternate signal to measure its received signal power when the signal from the active antenna fades below a selected threshold, or when the time since measuring the signal power from the opposite antenna exceeds the time coherence of the channel. One or

30   more embodiments of the receiver system also include adaptive algorithms that perform channel estimation and analyze Doppler shift. A switched-LNA dual diversity receiver system constructed in accordance with the described embodiments greatly improves performance over conventional systems in stationary and slow moving environments.

In one embodiment, a dual diversity receiver is provided that includes two antennas to receive a radio signal, where each antenna produces an antenna signal that is representative of the received radio signal. The receiver comprises first and second LNAs that receive the respective antenna signals and output first and second amplified signals. The receiver also comprises logic to determine the stronger antenna signal and select one of the LNA outputs for processing by the receiver.

In one embodiment, a method is providing for operating a dual diversity receiver that includes two antennas to receive a radio signal, where each antenna produces an antenna signal that is representative of the received radio signal. The method comprises steps of providing first and second LNAs to receive and amplify the respective antenna signals, determining which antenna has the stronger antenna signal, selecting one of the LNA to output a signal for processing by the receiver, and repeating the steps of determining and selecting.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and the attendant advantages of the embodiments described herein will become more readily apparent by reference to the following detailed description when taken in conjunction with the accompanying drawings wherein:

Figure 1 shows a diagram of one embodiment of a dual diversity receiver system that includes two antennas, which feed two parallel RF receivers;

Figure 2 shows a diagram that illustrates the operation of a channel interleaver/de-interleaver;

Figure 3 shows graphs that illustrate how different independently fading signals are received at two antennas, and how those signals combine;

Figure 4 shows one embodiment of a radio frequency receiver;

Figure 5 shows a graph that illustrates the RMS level of a received signal subject to small-scale fading;

Figure 6 shows a diagram of one embodiment of a dual diversity receiver that comprises a pair of switched-LNAs;

Figure 7 shows a diagram of one embodiment of a switched LNA that comprises a bias generator;

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Figure 8 shows a diagram of one embodiment of two switched LNAs and logic to provide complementary switching signals;

Figure 9 shows one embodiment of a method for use with one embodiment of a dual diversity receiver to adjust a selection signal (SEL) to activate the LNA receiving the stronger signal;

Figure 10 shows a diagram of one embodiment of first-order IIR digital filter used to perform a channel estimate;

Figure 11 shows a graph that illustrates an autocorrelation function of a typical Jake's spectrum fading process;

Figure 12 shows a diagram of one embodiment of a digital feedback circuit for the estimation of a Doppler frequency;

Figure 13 shows a diagram that illustrates the switching slot timing and other timing points associated with the method of Figure 9;

Figure 14 shows graphs that illustrate the benefits of selecting the stronger received signal using one embodiment of a dual diversity receiver using switched LNAs;

Figure 15 shows a graph that illustrates the frame error rate versus received signal power for a single antenna receiver and one embodiment of a dual diversity receiver in a vehicle at a speed of 3 km/hr;

Figure 16 shows a graph that illustrates the frame error rate versus received signal power for a single antenna receiver and one embodiment of a dual diversity receiver in a vehicle at a speed of 25 km/hr; and

Figure 17 shows a graph that illustrates the frame error rate versus received signal power for a single antenna receiver and one embodiment of a dual diversity receiver in a vehicle at a speed of 50 km/hr.

DETAILED DESCRIPTION

A dual diversity receiver system uses two antennas to combat small-scale fading effects. Although the two antennas receive the same set of multipath rays, the vector sum of the rays differs at each antenna. If the distance between the two antennas is large enough, the signals received by them undergo independent fading, thereby reducing the probability that both received signals are weak.

Figure 1 shows a diagram of one embodiment of a dual diversity receiver system that includes two antennas, which feed two parallel RF receivers. After baseband conversion, the two antenna signals undergo baseband processing (BB) and joint demodulation (combining or switching, channel decoding and data detection). The dual

5   diversity receiver duplicates the RF and baseband receivers, and thereby doubles the power, cost, and area used. It would therefore be advantageous to combine the signals (or switch between them) as close to the antennas as possible.

Wireless communication systems rely on the radio interface, which by its nature, places fundamental limits on performance. The quality of the radio interface, also known

10   as the radio channel, depends on several factors. This is because the path from the transmitter to the receiver is oftentimes not direct (line of sight). As such, the transmitted signal experiences reflection, diffraction, and scattering. These mechanisms create multiple signals (multipath signals) that travel along different paths of varying lengths, producing different phase offsets.

15   The multipath signals add vectorially at the receiving antenna. As such, it is possible for the multipath rays to combine destructively and for the received signal to virtually disappear for short periods of time. In a stationary environment, the received signal power follows a spatial function, and as such, the received signal power can vary significantly over very short distances. In an environment where the transmitter, receiver,

20   or other obstructions are moving, spatial fading variations result. These variations translate to time variations that depend on the relative speed of the objects. Furthermore, the relative motion of the objects creates random frequency modulation due to differing Doppler shifts.

The Doppler shift f_d can be positive or negative and is equal to:

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$$f_d = \frac{v}{\lambda}\cos\theta$$

where v is the relative velocity, λ is the wavelength of the transmitted signal, and θ is the angle associated with the transmitted path. The Doppler shift produces small-scale variations that map directly to the impulse response of the radio channel. Although the resulting impulse response changes, it remains relatively constant for a time period

30   known as the coherence time $(\Delta t)_c$, which is approximately equal to:

$$(\Delta t)_c = \frac{1}{f_d} \sim \frac{9\lambda}{16\pi v}$$

where λ/v represents the maximum Doppler shift. This is important because the coherence time also indicates the length of time a received signal experiences fading.

An effective countermeasure against fading is *diversity*, which can take many forms, such as time, frequency, and space diversity. All have in common the feature of sending two or more copies of the transmitted signal through channels affected by independent fading, and then combining or selecting the received signal replicas. The independent channels reduce the joint probability that the received signal experiences deep fading, thereby enhancing the performance of the communication system.

A channel interleaver/de-interleaver can be used to exploit time diversity by separating the bursts of consecutively faded symbols over different radio frames so as to make them easily correctable by the channel code. In other words, it scrambles the data in a way that distributes burst errors when the data is reordered at the receiver.

Figure 2 shows a diagram that illustrates the operation of a channel interleaver/de-interleaver. Interleaving performs well for fast-fading channels characterized by large Doppler shifts. For example, as illustrated in Figure 2, burst errors in the received data can be recovered when the data is reordered

Slow-fading channels do not benefit from time diversity and therefore require another form of diversity to improve performance. Spatial diversity using dual receiving antennas is one such technique. This takes advantage of small-scale effects that cause the power of the received signal to vary over small distances. As such, the received power of two different antennas, separated by a fraction of a wavelength, differs.

Figure 3 shows graphs that illustrate how different independently fading signals are received at two antennas, and how those signals combine. This effectively reduces the probability that both antennas receive deeply faded signals simultaneously.

Figure 4 shows one embodiment of a radio frequency (RF) receiver. The radio receiver comprises a low noise amplifier (LNA) to interface to the antenna, downconversion mixers (M1, M2) to translate the radio signal to baseband, and various analog circuits to filter, amplify, and convert the baseband signal to digital format. Two orthogonal channels (generated by in-phase and quadrature-phase local oscillator signals

derived from a PLL drive the downconversion mixers) preserve the phase of the modulated signal. An automatic gain control (AGC) signal provided by an AGC circuit (not shown) provides feedback, via a feedback loop, to the radio receiver's variable gain amplifiers (VGAs) to adjust the signal level applied at the A/D converters input. The

5   AGC operates on the root-mean-square (RMS) value of the received signal.

Figure 5 shows a graph that illustrates the RMS level of a received signal that is subject to small-scale fading. For example, the receiver shown in Figure 4 may receive the signal illustrated in Figure 5. The received signal is described by a relative signal strength indicator (RSSI) and defined by:

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$$RSSI_k = \sqrt{v_{I,k}^2 + v_{Q,k}^2}$$

where $v_{I,k}$ and $v_{Q,k}$ are the in-phase and quadrature-phase sample levels at time k quantized by the A/D converters. The feedback loop also includes simple low pass filters to ensure that the AGC ignores fast fading signals and acts on the average RMS level.

15   The sampled, integer-valued outputs from the A/D converters connect to the baseband receivers, which perform operations in the digital domain that depend on the particular signal format. For TDMA and FDMA systems, the filters comprise match filters. For direct-sequence code division multiple access (DS-CDMA) schemes, the matched filters are followed by a Rake receiver that performs despreading/descrambling

20   and multipath combining.

As illustrated in Figure 1, the dual diversity receiver comprises a second antenna and duplicates the complete signal-processing path from the received radio signals to the soft outputs from the matched filter or Rake receiver. After independent RF and baseband processing, the signal samples from the two antennas need further processing to

25   take advantage of their diversity. This can be done either by a suitable combining algorithm or by a switching algorithm that selects the stronger signal.

Figure 6 shows a diagram of one embodiment of a dual diversity receiver **600** that comprises a pair of switched-LNAs (LNA1, LNA2) and thus greatly simplifies the RF and baseband complexity of the receiver. The receiver **600** further comprises a selection

30   algorithm performed by selection logic (SEL Logic) that selects and periodically verifies the stronger received signal. For example, the selection logic operates to verify which of

the two antennas is providing the stronger signal. The selection logic may be implemented in hardware, software or any combination thereof. For example, the selection logic may comprise hard logic, a processor, gate array or any other suitable hardware and/or software to implement the selection algorithm.

5   Figure 7 shows a diagram of one embodiment of a switched LNA **700** that comprises a bias generator. For example, the LNA **700** may be used as LNA1 and LNA2 in the receiver **600** shown in Figure 6. The switched LNA consists of a common emitter amplifier (Q1) with inductive degeneration (L_2) and a tuned output load (L_1, C_1, and R_1). The inductive degeneration provides two benefits – it introduces linear feedback and also

10   increases the real part of the amplifier's input impedance, easing input matching. The bias generator sets the operating current of the LNA and transistor Q_1 equal to:

$$I_{C1} \sim \frac{A_{E1}}{A_{E2}} I_{C2}$$

where I_C and A_E are the collector current and emitter area of transistors Q_1 and Q_2. Note that the collector current I_{C2} approximately equals the reference current I_1 in the bias

15   generator. MOS transistors N_1 and N_2 provide a simple and effective way to disable the LNA. Turning on these devices, shunts the reference current I_1 to ground and nulls the base-emitter voltage applied to transistor Q_1.

The dual diversity receiver (i.e., receiver **600**) utilizes two switched LNAs, which share the same tuned output load. Only one LNA is active at any given time so that the

20   quiescent current flowing through the load is relatively constant. This is easily accomplished by using complementary switching signals to drive the separate bias generators associated with each LNA.

Figure 8 shows a diagram of one embodiment of two switched LNAs and logic to provide complementary switching signals. During operation, the select signal (*SEL*)

25   activates LNA1 when low and activates LNA2 when high. For example, the SEL signal may be generated by the SEL logic shown in Figure 6. The response of the bias generator when activated is dampened to prevent overshoot of the LNA's operating current.

Figure 9 shows one embodiment of a method **900** for use with one embodiment of

30   a dual diversity receiver (comprising switched LNAs) to control the selection signal

(SEL) in a way that activates the LNA receiving an antenna signal having a selected signal characteristic. For example, in one embodiment, the selected signal characteristic is signal strength, so that the LNA receiving the stronger signal is selected. For example, in one embodiment, the method comprises an algorithm implemented by the SEL logic

5   shown in Figure 6. For example, the SEL logic generates a SEL signal to control the operation of the two LNAs.

The method starts (block **902**) when the estimated coherence time $(\Delta t)_c$ (inverse of the Doppler spread) of the wireless channel exceeds the threshold λ. This indicates that the channel's response is changing slowly and the time diversity benefit associated with

10   interleaving is waning.

At block **904**, the coherence time is measured continuously and translated to a parameter L, which is equal to:

$$L = \left\lfloor \frac{(\Delta t)_c}{T_S} \right\rfloor$$

where T_S is a switching slot time, equal to the time needed to activate the opposite LNA

15   and measure its received power level, and the symbol $\lfloor x \rfloor$ is the *integer part of* x.

During operation, the method utilizes accurate estimates of the channel and the Doppler frequency. In one embodiment, a first-order infinite impulse response (IIR) digital filter is used to perform the channel estimate $(\Delta t)_c$.

At block **906**, in order to rapidly and reliably estimate the received signal power

20   at start-up and after switching to a new active antenna, the parameter K is made variable. A *reset* signal initializes the value of K to 1, so that the first output of the IIR digital filter coincides with the first input. K is then incremented (1, 2, 3, ...) to provide a smoothed channel estimate with:

$$y_k = \frac{1}{K}(x_k - y_{k-1}) + y_{k-1} = \frac{1}{K}\sum_{i=1}^{k} x_i$$

25   During operation, the parameter K is incremented (at block **910**) until the factor $1/K$ falls below a minimum value that depends on the Doppler frequency and corresponds to the steady-state response of the filter.

The power level received by the newly activated LNA is monitored over the switching slot, as shown at block **908**. The dual diversity algorithm then identifies the

stronger signal and stores the received power of the weaker signal as δ (block **912**). If necessary, the LNAs are switched to activate the LNA associated with the stronger received signal (block **914**). This LNA remains active until either of the following conditions at blocks **916** and **918** are satisfied:

$$\mathrm{P}_{RX} \leq \delta \qquad\qquad k \geq L$$

where P_{RX} is the measured received level and k is used to count the number of switching slots that have passed since the weaker received signal was measured. When either of these conditions is satisfied, the opposite LNA is switched and a new power measurement is made. This is then compared with the previous power measurement.

It should be noted that the method **900** illustrates just one embodiment and that changes, additions, or rearrangements of the method steps may be made without deviating from the scope of the invention.

Figure 10 shows a diagram of one embodiment of a first-order IIR digital filter **1000** used to perform the channel estimate. The input x to the digital filter **1000** is a noisy estimate of the channel amplitude and y is the improved, averaged estimate. The initial estimate x is dependent upon the communication system and is therefore found in different ways. For WCDMA systems, the pilot channel is analyzed, whereas for other systems (like GSM) a suitable preamble or mid-amble of known symbols is used. The IIR filter **1000** has a bandwidth that depends on a parameter K, which matches the speed at which the channel varies to improve the accuracy of the smoothed estimate y. The parameter that determines this speed is the *channel coherence time,* which is related to the Doppler frequency.

To simplify the fixed-point implementation of the channel estimation filter, the constant K is chosen to be a power of two, i.e.

$$K = 2^n$$

so that the multiplication by $1/K$ simply corresponds to shifting the input value by n positions to the right. In this case, the exponent n can only assume integer values, which are chosen so that the sequence of K approximates the sequence of integers (1,2,3,4, ...). The preferable sequence of n is therefore 0,1,2,2,2,3,3,3,3,3, ...

The estimate of the Doppler frequency f_D is an important task in wireless receivers as it determines the bandwidth of the (digital) filter that performs channel

estimation. In one or more embodiments, a simple, innovative algorithm is used to evaluate the Doppler frequency. It is based on the analytical expression of the autocorrelation function of the fading process expressed as:

$$R(t) = J_0\left(2\pi f_D t\right)$$

5 and depends on the Bessel function J_0 as plotted in Figure 11. The fading process is typically simulated using Jake's model.

The first zero of the autocorrelation function (corresponding to the argument of 2.4048) yields the following relationship between the minimum interval t_0 between two uncorrelated fading samples and the Doppler frequency:

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$$f_D = \frac{2.4048}{2\pi t_o} = \frac{0.3827}{t_0}$$

and thus allows an estimate of the Doppler frequency through a digital feedback circuit that measures t_0, as shown in Figure 12.

The initial complex estimates x of the channel are sampled with a period corresponding to the current stored value t_0. The sample is multiplied by the complex

15 conjugate of the previously stored value, and the sign of the real part of the result is used to update the estimation t_0. The update step for the estimate is given by Gt_0, where the constant G is chosen to stabilize the loop and provide the desired accuracy. As a result, the step size depends upon t_0, and this advantageously increases the estimation speed when the Doppler frequency (and updating frequency) is very low.

20 The initial values for t_0 should be small enough to ensure that the initial sampling of the fading process is frequent enough and to prevent the circuit from locking onto zeroes of the autocorrelation function other than the first one. Also, it is effective to limit the maximum value of t_0, and thus the minimum value of the Doppler frequency f_D, in order to improve the tracking capabilities of the circuit.

25 Figure 13 shows a diagram illustrating the timing associated with the dual diversity receiver. The dual diversity algorithm continues to run as long as the coherence time exceeds a second threshold μ, set to a value less than $\lambda\square$, to introduce hysteresis. As shown in Figure 13, the selection signal (SEL) controls the operation of the LNAs.

Figure 14 shows graphs that illustrate how in one or more of the embodiments,

30 the dual diversity receiver increases the minimum power level and thereby improves the

signal-to-noise ratio (*SNR* or equivalently E_b/N_o) of the received signal. This is accomplished this by selecting the stronger of two received signals and verifying this against two criteria.

The performance of the dual diversity receiver using switched LNAs and the associated selection algorithm was simulated for application in WCDMA communication systems. The communication channel was modeled as three Rayleigh-distributed fading components with equal power and propagation delays of 0, 3.75, and 76.92 μsec, respectively. The switching slot time was set to 1 msec. The mobile receiver was moving at speeds of 3, 25, and 50 km/hr.

Figures 15, 16 and 17 compares the received signal power of a single antenna receiver and one embodiment of a dual diversity receiver as described herein. These performance curves illustrate the benefits of the switched antenna dual diversity receiver operating in a vehicle at vehicle speeds of 3, 25 and 50 km/hr. In the graphs, the received signal from the dual diversity receiver is always the curve on the left side. Note that 3dB improvement was observed at the slowest speed and approximately 1dB improvement was measured at the highest vehicle speed.

In one or more embodiments, a dual diversity receiver using switched LNAs and an innovative selection algorithm has been described. During operation, the receiver activates the LNA and antenna associated with the stronger received signal to take advantage of spatial diversity. The algorithm requires the estimate of the two antenna channels and of the Doppler frequency. Two innovative digital circuits to perform both estimates have been described. As a result, improved performance is realized with a very efficient radio architecture that requires only a second switched LNA, thereby providing power, cost, and area improvements as compared to conventional receivers. It is also possible to incorporate embodiments of the invention into receiver systems having more than two antennas. Based on the above disclosure, such incorporation could be implemented by one with knowledge of receiver systems.

Accordingly, while one or more embodiments of methods and/or apparatus for a dual diversity receiver system have been illustrated and described herein, it will be appreciated that various changes can be made to the embodiments without departing from their spirit or essential characteristics. Therefore, the disclosures and descriptions herein

are intended to be illustrative, but not limiting, of the scope of the invention, which is set forth in the following claims.

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